

V2653 Ophiuchii with a pulsating component and P_{puls} - P_{orb} , P_{puls} - g correlations for γ -Dor type pulsators

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Abstract

We present new spectroscopic observations of the double-lined eclipsing binary V2653 Oph. The photometric observations obtained by *ASAS* were analysed and combined with the analysis of radial velocities for deriving the absolute parameters of the components. Masses and radii were determined for the first time as $M_p=1.537\pm0.021 M_\odot$ and $R_p=2.215\pm0.055 R_\odot$, $M_s=1.273\pm0.019 M_\odot$ and $R_s=2.000\pm0.056 R_\odot$ for the components of V2653 Oph. We estimate an interstellar reddening of 0.15 ± 0.08 mag and a distance of 300 ± 50 pc for the system, both supporting the membership of the open cluster Collinder 359. Using the out-of-eclipse photometric data we have made frequency analysis and detected a periodic signal at 1.0029 ± 0.0019 c/d. This frequency and the location of the more massive star on the HR diagram lead to classification of a γ Dor type variable. Up to date only eleven γ Dor type pulsators in the eclipsing binaries have been discovered. For six out of 11 systems, the physical parameters were determined. Although a small sample, we find empirical relations that $P_{puls} \propto P_{orb}^{0.43}$ and $P_{puls} \propto g^{-0.83}$. While

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the pulsation periods increase with longer orbital periods, they decrease with increasing surface gravities of pulsating components and gravitational pull exerted by the companions. We present, briefly, the underlying physics behind the correlations we derived.

Keywords: Stars: fundamental parameters – individual: V2653 Oph – binaries: eclipses – –

1. INTRODUCTION

Main-sequence and subgiant stars of spectral type A to F in detached and semi-detached eclipsing binaries are very interesting targets for asteroseismic studies, i.e., the determination of the boundaries of instability strip by interpreting the observed oscillation characteristics. Indeed, eclipsing binaries containing A-F stars offer the possibility of determining accurate masses and radii for the components. Unique advantage is if the binary resides in a cluster, determination of the fundamental properties and, in particular for systems belonging to the open clusters, can be used to address relevant astrophysical issues, such as chemical compositions, age and the distance of two stars with accurate masses and radii, allowing a much more discriminating test of physical ingredients of theoretical models.

We present a study of the detached *Algol* type eclipsing binary, which is probably a member of the open cluster Collinder 359 (Zejda et al., 2012). We have obtained complete light curves from the photometry obtained by *Hipparcos* (Perryman et al., 1997) and All Sky Automated Survey, ASAS, (Pojmanski, 2002). We have also obtained an extensive spectroscopy using the FRESCO échelle spectrograph at the telescope of Catania Astrophysical

Observatory.

Ochsenbein (1980) measured the visual magnitude of 8.90 mag with a precision of one tenth of a magnitude and a color of G5 using "microfiche" photographic observations for V2653 Oph. The eclipsing character of V2653 Oph (HD 162811; BD+03°3514; HIP 87511; $V=9.49$, $B-V=0.60$ mag)¹ was discovered by the *Hipparcos* satellite mission, the primary eclipse having an amplitude of 0.09 mag. The depth of the secondary minimum is nearly equal to that of the primary one. The first eclipse light curve was roughly revealed by the *Hipparcos* observations. Kazarovets et al. (1999) designated it as V2653 Oph in the 74TH NAME-LIST OF VARIABLE STARS, and classified it as an eclipsing binary. In recent years, large-scale photometric surveys, such as All Sky Automated Survey (ASAS) (Pojmanski, 1997), *MOST* (Walker et al., 2003), *CoRoT* (Baglin et al., 2009), *Kepler* (Gilliland et al., 2010), etc. have been conducted with the main aim of looking for transiting exoplanets. The valuable by-product of this search has been the very large number of well sampled eclipsing binary light curves. One of the eclipsing binaries observed at the Las Campanas Observatory as part of the ASAS was V2653 Oph. Yet the astrophysical parameters are not obtained for the system.

2. Observation and data reduction

The 91-cm telescope of the Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania (INAF–OACT) was used to carry out spectroscopy of the target. Details of the telescope and the echelle spectrograph are given

¹adopted from the SIMBAD astronomical data base.

by Çakırlı et al. (2008). Observations were carried out during eleven nights between 21 June - 05 July 2008. Exposure times were fixed for target star at 2400 s.

The reduction of the spectra was done by using the NOAO/IRAF package². The *Th-Ar* emission line spectra were used to calibrate the wavelength references of each observations. The S/N ratio of the spectra was at least ~ 90 .

Photometric observations of the system obtained and published in ASAS-3 were used to construct the V-band light curve. For calculation of the orbital phases we tried to improve a better epoch and an orbital period for the system. An orbital period of about 4.394 days was estimated from the photometric observations of the system by the *Hipparcos* mission. We searched for orbital period using data combined from the *Hipparcos* and ASAS surveys. Analysis of Variance (AoV) algorithm developed by Schwarzenberg-Czerny (1989) and implemented in the VarTools light curve analysis program (Hartman et al., 2008) was used for detection of sharp periodic signals. We obtained the period and *False Alarm Probability* of peaks which are significant at a level greater than 3σ . We detect significant peaks in the power spectra at periods between 2–5 days, the most significant being at 4.39 days. We improved the light elements of the system using the Wilson-Devinney code (Wilson & van Hamme, 2003). The light and radial velocity curve of the system is phased with the following ephemeris and period:

²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc.

$$T_{\text{minI}} = 2453189.668(58) + 4^d.3942894(48) \times E. \quad (1)$$

The orbital period is very close to that estimated by Otero et al. (2005). The radial velocities and photometric observations were phased using these light elements.

3. Spectroscopic data

3.1. Radial velocity analysis

Radial velocities (RV) of the components were derived with a standard cross correlation algorithm, IRAF's tool FXCOR. We used the wavelength interval 4500 – 5000 Å, which is rich in metallic lines. As cross correlation template, we chose the nearby primary target ι Psc (F7 V) of similar spectral type and we used, for reference, as the RV standard. The radial velocities of the components were derived by fitting two Gaussian curves with the FXCOR function and presented in Table 1. The radial velocities were analysed using the RVSIM software program (Kane, Schneider, & Ge, 2007). The parameters are presented in Table 2 and the fits are compared with the observations in Fig. 1.

3.2. Determination of the atmospheric parameters

The width of the cross-correlation function (CCF) is a good tool for the measurement of $v \sin i$ of a star. We used a method developed by Penny (1996) to estimate the $v \sin i$ of each star composing the investigated double-lined eclipsing binary system from its CCF peak by a proper calibration based on a spectrum of a narrow-lined star with a similar spectral type.

Table 1: Heliocentric radial velocities of V2653 Oph. The columns give the heliocentric Julian date, orbital phase and the radial velocities of the two components with the corresponding standard deviations.

HJD-2400000	Orbital	V2653 Oph			
	Phase	V_P	σ	V_S	σ
54638.34598	0.6729	84.2	0.6	-83.2	0.7
54639.33703	0.8984	44.2	0.9	-55.4	0.7
54640.33176	0.1248	-81.2	1.1	55.6	1.1
54641.34108	0.3545	-81.2	0.9	51.4	0.4
54642.34823	0.5837	50.1	1.1	-55.3	1.1
54643.35360	0.8124	81.5	1.0	-84.3	0.6
54644.38749	0.0477	-41.3	1.4	21.2	0.7
54647.37993	0.7287	92.4	0.7	-88.5	0.7
54649.36320	0.1800	-100.2	0.8	66.5	1.2
54651.35779	0.6339	71.4	0.8	-71.2	1.3
54654.34120	0.3129	-95.6	0.7	66.2	1.1

Table 2: Results of the radial velocity analysis for V2653 Oph.

Parameter	V2653 Oph	
	Primary	Secondary
K (km s ⁻¹)	83±1	93±1
V_γ (km s ⁻¹)	-8.41±0.43	
Average O-C (km s ⁻¹)	0.5	0.9
$a \sin i$ (R_\odot)	15.9±0.1	
$M \sin^3 i$ (M_\odot)	1.50±0.10	1.25±0.18
e	0.0	

The rotational velocities of the components were obtained by measuring the FWHM of the CCF peak related to each component in five high-S/N spectra acquired near the quadratures, where the two spectra have the largest relative difference in radial velocity. The CCFs were used for the determination of $v \sin i$ through a calibration of the full-width at half maximum (FWHM) of the CCF peak as a function of the $v \sin i$ of artificially broadened spectra of a slowly rotating standard star (ι Psc, $v \sin i \simeq 3 \text{ km s}^{-1}$, e.g., Takeda et al. 2005) acquired with the same set up and in the same observing night as the target system. The limb darkening coefficient was fixed at the theoretically predicted values, 0.55 for the system (van Hamme, 1993). We calibrated the relationship between the CCF Gaussian width and $v \sin i$ using the Conti & Ebbets (1977) data sample. This analysis yielded projected rotational velocities for the components of V2653 Oph as $v_p \sin i = 25 \text{ km s}^{-1}$, and $v_s \sin i = 20 \text{ km s}^{-1}$. The mean deviations were 1 and 2 km s^{-1} , for the primary and secondary, respectively, between the measured velocities for different lines.

In Fig. 2 we show the simulation of the spectrum of the system with that of broadened combination of the two standard spectra at phase 0.72 (HJD 54647.37993) using the derived rotational velocities. The spectral order at blue wavelength is displayed. The sum of residuals is also shown, as a function of $v \sin i$, in the insets of Fig 2.

We also performed a spectral classification for the components of the system using the COMPO2, an IDL³ code for the analysis of high-resolution

³Interactive Data Language, ITT 1997

Table 3: Spectral types, effective temperatures, surface gravities, metallicity and rotational velocities of components estimated from the spectra of V2653 Oph.

Parameter	V2653 Oph	
	Primary	Secondary
Spectral type	F(2 \pm 0.5) V	F(7 \pm 0.5) V
T_{eff} (K)	6 950 \pm 480	6 350 \pm 650
$\log g$ (<i>cgs</i>)	4.07 \pm 0.02	4.22 \pm 0.06
$v \sin i$ (km s $^{-1}$)	25 \pm 1	20 \pm 2
[<i>Fe/H</i>] (dex)	-0.11 \pm 0.08	0.07 \pm 0.09

spectra of eclipsing binary systems originally written by Frasca et al. (2006) and adapted to the REOSC spectra. This code searches for the best combination of two reference spectra able to reproduce the observed spectrum of the system. We give, as input parameters, the radial velocities and projected rotational velocities of the two components of the system, which were already derived. The code then finds, for the selected spectral region, the spectral types and fractional flux contributions that best reproduce the observed spectrum, i.e. which minimize the residuals in the collection of difference (observed – composite) spectra. For this task we used reference spectra taken from the Valdes et al. (2004) *Indo–U.S. Library of Coude Feed Stellar Spectra* (with a resolution of $\approx 1\text{\AA}$) that are representative of stars with spectral types from late-O type to early-M, and luminosity classes V, IV, and III. The atmospheric parameters of these reference stars were recently revised by Wu et al. (2011).

We selected 198 reference spectra spanning the ranges of expected atmo-

spheric parameters, which means that we have searched for the best combination of spectra among 39 204 possibilities per spectrum. The observed spectra of V2653 Oph in the $\lambda 4960$ – 5000 spectral region were best represented by the combination of HD 183085 (F0.5 V) and ι Psc (F7 V). However, we have adopted, for each component, the spectral type and luminosity class with the highest score in the collection of the best combinations of templates, where the score takes into account the goodness of the fit expressed by the minimum of the residuals. We have thus derived a spectral types for the primary and secondary component of V2653 Oph as F2 and F7 main-sequence stars, with an uncertainty of about 0.5 spectral subclass. The effective temperature and surface gravity of the two components of the system are obtained as the weighted average of the values of the best spectra at phases near to the quadratures combinations of templates adopting a weight $w_i = 1/\sigma_i^2$, where σ_i is the average of residuals for the i -th combination. The standard error of the weighted mean was adopted for the atmospheric parameters. The atmospheric parameters obtained by the code and their standard errors are reported in Table 3. The observed spectra of V2653 Oph at phase near to the quadrature is shown in Fig. 2 together with the combination of two reference spectra which gives the best match and their residuals.

3.3. Spectroscopic light ratio

For the detached eclipsing binaries, where the temperature of the two stars are closely similar, the light ratio can be calculated from the cross-correlation functions (CCF) of the various spectra. Çakırlı et al. (2008) showed, by measuring the average fitted full width half maximum (FWHM) values of the echelle orders in the selected spectral domains, which include

several photometric absorption lines. In this study we have disregarded very broad lines, such as H_β and H_α , because their broad wings affect the CCF and lead to large errors. Inspection of the CCFs showed that the two components are visible and well separated from each other near the quadratures. Following the method proposed by Çakırlı et al. (2008), the two-Gaussian fits of the well-separated CCFs using the de-blending procedure in the IRAF routine SPLOT. The average fitted FWHMs are 120 ± 2 and 65 ± 3 km s^{-1} for the primary and secondary components. Fig. 3 shows a sample of the double-Gaussian fit. Indeed, the shapes and velocities corresponding to the peaks of the CCFs are slightly changed. We estimated the intensity ratio $\ell_1 / (\ell_1 + \ell_2) = 0.649 \pm 0.032$ from the two-Gaussian fits of the well-separated CCFs.

4. Light curve analysis

The photometric data collected from the ASAS catalogue. We analyzed the light curve using the Wilson-Devinney code (hereafter WD; e.g., Wilson & Devinney, 1971; Wilson, 1979; Wilson & van Hamme, 2003; Wilson, 2006) implemented into the software PHOEBE (Prša & Zwitter, 2005). The WD code is widely used for determination of the orbital parameters of the eclipsing binaries. To run the code we need some initial parameters. The initial logarithmic limb-darkening coefficients were taken from the tables given by van Hamme (1993) as $x_1 = 0.47$ and $x_2 = 0.48$, and are automatically interpolated at each iteration by PHOEBE. The effective temperature of the primary star is taken as 6950 K and the ratio of the masses of two components $q = 0.84$. We have started with *Mode* = 2 meant for detached binary

Table 4: Final solution parameters for the detached model of V2653 Oph.

Parameters	V2653 Oph
i°	81.78 ± 0.25
T_{eff_1} (K)	6 950[Fix]
T_{eff_2} (K)	$6\,540 \pm 1\,60$
Ω_1	8.048 ± 0.175
Ω_2	7.717 ± 0.183
r_1	0.1391 ± 0.0034
r_2	0.1256 ± 0.0035
$\frac{L_1}{(L_1+L_2)}$	0.613 ± 0.015
$\sum(O - C)^2$	0.188

systems, keeping the temperature of the primary and the mass-ratio as fixed parameters. According to the WD code we adjusted the following parameters: i (the orbital inclination), Ω_1 (the potential for the primary), Ω_2 (the potential for the secondary), T_{eff_2} (the effective temperature of the cool star), L_1 (the luminosity of the primary), and the zero-epoch offset. The luminosity of the secondary star, L_2 , was constrained by the model. After a few numbers of runs of the Differential Correction program in *Mode* – 2 the sum of residuals squared showed a minimum and the corrections to the adjustable parameters became smaller than their probable errors. The results are presented in Table 4. The corresponding computed light curve is shown in Fig. 4 as a continuous line.

5. Absolute dimensions

Combining the results of radial velocities and light curve analysis we have calculated the absolute parameters of the stars. The separation between the components of eclipsing pair is calculated as $a=15.98\pm0.07 R_{\odot}$. The fundamental stellar parameters for the components such as masses, radii, luminosities are listed in Table 5 together with their formal standard deviations. The standard deviations of the parameters have been determined by using the JKABSDIM⁴ code, which calculates distance and other physical parameters using several different sources of bolometric corrections (Southworth et al., 2005). The masses for the primary and secondary star are consistent with $F2\pm0.5V$ and $F7\pm0.5V$ stars.

The distance determination depends, of course, on the total apparent visual magnitude and the observed colour of the system. The observed visual magnitude of the system was estimated by various authors in the range from 9.48 (Mendoza et al., 1978) to 9.98 mag. (Hanson et al., 2004). Since the Tycho measurements include probable errors, e.g. $B_T=10.224\pm0.030$, $V_T=9.568\pm0.024$ mag, we adopt the apparent visual magnitude of 9.509 ± 0.027 mag and colour index of $(B-V)=0.558\pm0.082$ mag for the system, transformed from Tycho to Johnson photometric system using the coefficients given by Høg et al. (2000). Taking into account the de-reddened colour index of the primary star as 0.35 mag for an F2V star and the light ratio of $L_2 / L_1=0.63$ we estimated de-reddened colour index for the system as 0.405 mag. Then we estimated the interstellar reddening of $E(B-V)=0.15\pm0.08$ mag for the

⁴This can be obtained from <http://http://www.astro.keele.ac.uk/~jkt/codes.html>

Table 5: Absolute properties of the V2653 Oph components

Parameter	Primary	Secondary
Mass (M_{\odot})	1.537 ± 0.021	1.273 ± 0.019
Radius (R_{\odot})	2.215 ± 0.055	2.000 ± 0.056
T_{eff} (K)	$6\,950 \pm 480$	$6\,350 \pm 650$
$\log (L/L_{\odot})$	1.014 ± 0.122	0.820 ± 0.175
$\log g$ (<i>cgs</i>)	3.934 ± 0.021	3.941 ± 0.024
<i>Sp.Type</i>	F(2 \pm 0.5) V	F(7 \pm 0.5) V
M_{bol} (mag)	2.21 ± 0.31	2.69 ± 0.44
<i>BC</i> (mag)	0.030	0.009
M_V (mag)	2.18 ± 0.33	2.69 ± 0.48
$(v \sin i)_{calc.}$ (km s $^{-1}$)	25.5 ± 0.6	23.0 ± 0.7
$(v \sin i)_{obs.}$ (km s $^{-1}$)	25 ± 1	20 ± 2
d (pc)	284 ± 45	321 ± 73

system. The bolometric corrections are adopted from Flower (1996) for the primary and secondary stars. The absolute bolometric magnitude of the Sun is taken as 4.74. The distance to the system is estimated as 300 ± 50 pc. The weighted mean distance calculated from the individual distances given in Table 5 is 298 ± 56 pc, consistent with the distance estimated from total apparent visual magnitude and interstellar reddening of the system. As it is known that the distance measured by the *Hipparcos* becomes inaccurate for $d>100$ pc.

V2653 Oph is located, on the sky, very close to the centre of the Collinder 359 open cluster. Recently Zejda et al. (2012) presented the first new catalog of known variable stars in open cluster regions. They have proposed that V2653 Oph is a probable member of the Collinder 359. However, its membership to the Collinder 359 is still uncertain. The systemic velocity of the V2653 Oph, -8.4 km s^{-1} , is consistent with the measured cluster systemic velocities of Plaskett & Pearce (1931), Nordström et al. (2004) and Gontcharov (2006). Interstellar reddenings for the stars in the cluster were estimated as of 0.16 mag obtained by Kharchenko (2001) and 0.191 mag Zejda et al. (2012). The distance of the Collinder 359 is still uncertain. Distance determination is in general based on isochrone fitting of early type stars. For Collinder 359 listed 13 cluster members by Collinder (1931) and estimated a distance to the cluster ranging from 210 pc to 290 pc. Later, Rucinski (1987) made UBVRI photometry and obtained a distance to the cluster about 436 pc, rejecting half of the original members. Trigonometric parallaxes of five photometric members were measured by *Hipparcos* satellite which yielded distances between 260 pc and 280 pc for Collinder 359. The systemic velocity, interstellar

reddening and distance of V2653 Oph are in good agreement with those derived for the cluster. It seems highly probable that V2653 Oph does belong to Collinder 359.

The age determined for the Collinder 359 has changed dramatically since the early determination by Wielen (1971) of 20 to 50 Myr. Later studies derived 30 Myr (Abt, Bollinger, & Burke, 1983). Both results are in agreement and consistent with the more recent values range from 50 Myr (Baumgardt, Dettbarn, & Wielen, 2000; Kharchenko, 2001). Jeffries & Naylor (2001) put an upper limit of 100 Myr on the age of Collinder 359 using the lithium test described by Rebolo et al. (1996). Comparison with the various evolutionary tracks indicates that the components of V2653 Oph have an age of about $300(\pm 100)$ Myr, older than the cluster. If the binary is really a member of the cluster its age should be at least three times older than the values estimated up to date.

6. γ Dor type variables in close binary systems

Fig.4 shows that there is a considerable light variations at outside of eclipses. The γ Dor type pulsating single stars and components in the eclipsing binaries were plotted in the $\log T_{eff}-\log L/L_{\odot}$ plane and shown in Fig.5. The empty symbols show the single stars taken from the catalog of Henry, Fekel, & Henry (2007) while the filled circles indicate the γ Doradus type pulsators in the eclipsing binaries. The primary component of V2653 Oph locates in the instability strip of γ Doradus type variable stars. The known γ Dor type pulsating variables in the eclipsing variables are: V551 Aur, VZ CVn, V2094 Cyg, V404 Lyr, Corot 100866999, Corot 102918586,

Corot 102937335, Corot 102980178, KIC 04544587, KIC 11285625.

The γ Doradus and δ Scuti type pulsators share a similar parameter space in the Hertzsprung-Russell (HR) diagram. While the δ Sct stars are believed to be mostly low-radial-order pressure mode pulsators (Breger, 2000), the γ Dor stars are high-radial-order gravity mode pulsators (Kaye et al., 1999). Handler & Shobbrook (2002) showed that the δ Sct and γ Dor type pulsating stars are separated by the values of their pulsation constants. While the δ Sct pulsators have pulsation constant of $Q \sim 0.03$ days, the known γ Dor pulsators all have $Q > 0.23$ days.

Therefore, we started to search any periodic light variations in the system. To investigate the intrinsic light variations of the components in eclipsing binary systems, the best-fit binary star model was subtracted from the light curve. This leaves the stellar pulsations, random noise, systematic calibration noise, and any slight mismatches between the model and actual binary star light curve. In these circumstances, frequency analysis was performed on the residuals of the system, in the region $0\text{--}3\text{ d}^{-1}$, where the most of the dominant pulsation frequencies are found. In order to generate the frequency spectrum of residual data, shown in Fig. 6, we used `Period04`⁵. Figure 6 displays the amplitude spectra in the frequency range from 0.6 to 2.0 d^{-1} , γ Dor oscillation frequencies indeed are typically detected in this range (Balona et al., 2011).

The amplitude spectra after the analysis are presented in Fig. 6. Clearly visible is the only a peak around 1.0 d^{-1} . The light variation is dominated with a frequency $f_1=1.0029(19)$ and a full amplitude of about 60 mmag. The

⁵<https://www.univie.ac.at/tops/Period04/>

uncertainty of the frequency was derived according to Kallinger et al. (2008). No significant peaks are present in the region higher than 5 d^{-1} and smaller than 0.6 d^{-1} . One sees that V2653 Oph pulsates in the frequency range of γ Dor type variables (Grigahcène et al., 2010).

Investigation of γ -Dor type pulsating variables in close eclipsing binary systems is a relatively new area of the stellar astrophysics. The first γ Dor type pulsation was discovered by Ibanoglu et al. (2007) in the more massive primary star of the eclipsing binary system VZ CVn. Following this discovery new γ -Dor pulsators were revealed by precise photometric studies. We collected the eclipsing binaries with γ -Dor pulsators and presented in Table 6. So far, 11 eclipsing binary systems containing a γ -Dor type pulsating component have been discovered. Unfortunately, spectroscopic observations of only six systems have been made and precise radial velocities and, therefore, the orbital elements were determined. The number of γ -Dor type pulsators in the close binaries will be rapidly increased in a few years after the analyses of the huge precise data obtained by space missions such as *CoRoT*, *Kepler*, etc.

A decade ago Soydugan et al. (2006) suggested a linear relationship between the orbital and pulsation periods for the 20 δ -Sct type pulsators in the classic Algol type systems. This relationship based on observations is confirmed and refined by Liakos et al. (2012) using the data almost quadruple than that of Soydugan et al. (2006). The correlation between the pulsation (P_{puls}) and orbital (P_{orb}) periods has been theoretically established by Zhang, Luo, & Fu (2013). In Table 6 we present mass and radius (in solar units), mean density and surface gravity (in CGS units) and pulsation con-

stant (in days) for the pulsating stars in the eclipsing binaries, for which precise photometric and spectroscopic observations are available. The dominant pulsation periods are taken into account and the pulsation constants were calculated using these periods and mean densities. The pulsation constants vary between 0.17 and 0.72, systematically larger than the value of 0.033 days for the radial fundamental modes (Breger, 1990; Stankov& Handler, 2005).

In Fig. 7 we plot the dominate pulsation periods against the orbital ones, where the periods are in days. Even with a small sample, 11 systems at present, we claimed sufficient evidence of a correlation. One possible explanation would be that according to this empirical correlation, the longer the orbital period of a binary, the longer the pulsation period of its pulsating primary. The $P_{puls} - P_{orb}$ relation appears to be a simple linear form, the following numerical relation was obtained by linear least squares method,

$$\log P_{puls} = 0.425(\pm 0.016) \times \log P_{orb} - 0.355(\pm 0.087). \quad (2)$$

The correlation coefficient for this relationship is about 0.79, indicating its significance. The scatter appears to increase towards the shorter orbital periods.

Although the sample contains eleven pulsating primary stars and existence of a considerable scatter in the observed pulsation frequencies a connection between pulsation and orbital periods seems to exist in the γ -Dor type stars as pointed out by Soyduhan et al. (2006) for the δ -Sct stars. The pulsation periods are proportional to the orbital periods as $P^{0.43}$. This relation indicates that the shorter orbital period the smaller pulsation period. For the δ -Sct stars in close binaries Liakos et al. (2012) find a relationship as

P_{puls} proportional to $P_{orb}^{0.58}$.

Recently Zhang, Luo, & Fu (2013) indicated that the upper limit of P_{puls}/P_{orb} is about 0.09 for the δ -Sct stars. All the stars given in Table 6 have larger ratios than those of the δ -Sct stars except CoRot102980178. It has the smallest ratio with 0.072. This star is not clearly classified yet. It was classified as a γ -Dor pulsator by Sokolovsky et al. (2010), however, the classification as a **Slowly Pulsating B star** (SPB) could not be ruled out. There are some doubts about the classifications of V551 Aur and KIC04544587. Both the Q-values and period ratios lead to classification of γ -Dor type pulsation. The pulsational period is connected to the mean density in the pulsating variables. The period-mean density relationship can be written as:

$$P_{puls} = Q\sqrt{\rho_{\odot}/\rho} \quad (3)$$

where Q is the pulsation constant, ρ and ρ_{\odot} are the mean density of the star and the sun. The mean density is expressed by the mass and radius of the star. Then the above equation can be rearranged to the form:

$$P_{puls} = Q\sqrt{\frac{R_{puls}^3}{M_{puls}}} \quad (4)$$

where R_{puls} and M_{puls} are the radius and mass of the pulsating star. Solving the Kepler's Third law for the mass of the pulsator and inserting to the above equation we obtain,

$$P_{puls} = Q \times P_{orb} \times \left\{ G \times \frac{R_{puls}^3}{4\pi^2 \times a^3} \right\}^{\frac{1}{2}} \times \left\{ 1 - \frac{M_s}{M_{puls} + M_s} \right\}^{-\frac{1}{2}} \quad (5)$$

where P_{orb} is the orbital period, a is the semi-major axis of the eclipsing system's orbit and M_s is the mass of the secondary star and G is the Newton's gravitational constant. This expression indicates that the pulsational period of a pulsator in an eclipsing binary is depended up on the orbital period.

We also plot the pulsation periods against the gravities of the pulsating stars in Fig. 8, where the pulsational periods are in days and the gravities in CGS units. The open square in this figure shows V404 Lyr for which no radial velocities exist, the gravity is estimated from the preliminary mass and radius determined only from the light curves. Therefore it was not used in the calculation of the correlation between the pulsational period and gravity. Gravities were calculated for only six γ -Dor type pulsators in the close binaries for which radial velocities and photometric light curves exist. A preliminary least squares analysis yields a relationship between the pulsational period and gravity as,

$$\log P_{puls} = -0.828(\pm 0.076) \times \log g + 3.385(\pm 0.218) \quad (6)$$

with a correlation coefficient of 0.81. The pulsational periods are decreasing while the surface gravities are increasing, similar to the δ -Sct stars (dot-dashed line in Fig. 8) (Liakos et al., 2012) and to those all radially pulsating variable stars (dashed line) (Ferne, 1995). While the slope is about -3.3 for the δ -Sct stars, -0.88 for the radially pulsating variable stars. The pulsation periods of γ -Dor type pulsators seem to depend on the surface gravity similar to those radially pulsating variable stars proposed by Ferne (1995).

The gravitational force applied to per gram matter on the surface of the pulsating component can be determined by

$$g = G \times \frac{M_{puls}}{R_{puls}^2}. \quad (7)$$

Since P_{puls} depends on the R_{puls} and M_{puls} as given in Eq.4 we can easily obtain,

$$P_{puls} = Q \times G^{\frac{1}{2}} \times R_{puls}^{\frac{1}{2}} \times g^{-\frac{1}{2}} \quad (8)$$

The pulsational period is inversely proportional of the square root of the surface gravity of the pulsating star.

We also plot in Fig.9 the pulsational periods of the oscillating primary components against the gravitational pull exerted to the per gram of the matter on the surface of the pulsators by the less massive companions (in cgs units). The short orbital period binary VZ CVn appears to have longer pulsational period with respect to the gravitational pull of the companion. This star is significantly separated from the other stars. It has the greatest filling factor with 0.78 amongst the six stars (see Table 6). Excluding VZ CVn, the linear least-squares fit gives the following relationship,

$$\log P_{puls} = -2.021(\pm 0.012) \times \log(F/M_{puls}) + 2.093(\pm 0.098) \quad (9)$$

with a correlation coefficient of 0.83. The high-value of the correlation coefficient indicates that this empirical relationship is very significant. As the force per unit mass on the surface of the pulsating star applied by the companion star is increased the pulsational period is decreased. The force exerted to per gram matter on the surface of the pulsating star can be calculated as,

$$\frac{F}{M_{puls}} = \frac{GM_s}{(a - R_{puls})^2}. \quad (10)$$

Since $P_{puls} \propto R_{puls}^{3/2}$ we can obtain $P_{puls} \propto (\frac{F}{M_{puls}})^{-3/4}$. As the gravitational pull exerted on the per gram matter of the pulsator is increased the pulsational period is decreased, confirming the empirical relationship found.

Even with a small sample, pulsation periods of the γ -Dor type pulsators in the close binaries seem to depend on the orbital periods of the systems, to the surface gravities of the pulsating primaries, and also to the gravitational pull applied by their companions. These empirical relationships should, of course, be checked by increasing the number of the sample.

Although we are still at the beginning of understanding the whole extent of the γ Doradus phenomenon, but the combination of the current observational results and theoretical models are expected to answer a lot of open questions. Verification of the present results, especially for the low amplitude frequencies, the detection of the multi-frequencies, and the derivation of the excitation modes are some open questions on the class of γ Dor type asteroseismology. We strongly suggest that accurate photometric survey of these systems are needed for answering the listed open questions. Moreover, phase coverage of their light curves and radial velocities will provide their geometrical characteristics. Finally, high-resolution spectroscopy are also suggested not only for the pulsations, but also for the components' radial velocity curves, which will lead us to calculate their absolute properties with high accuracy.

7. Conclusion

V2653 Oph is a detached eclipsing binary in the young open cluster Collinder 359. It is composed of main sequence F type stars. We have derived the astrophysical parameters of the components and other properties for the first time, listed in Table 5, by combining the results obtained from the analyses of light curve and radial velocities. The masses and radii of the stars were derived with accuracy of 2 and 6 percent, respectively. Both components are well inside their corresponding Roche lobes. Both components show nearly synchronized rotation. Taking into account the total apparent visual magnitude of the system, the light contribution of the stars and the bolometric corrections given by Flower (1996) and Girardi et al. (2002) we calculated a mean distance to V2653 Oph as 300 ± 50 pc. The published parallax, measured by *Hipparcos* satellite is very uncertain, $\pi = 3.72 \pm 1.28$ mas, corresponding to a formal distance of 269^{+141}_{-68} pc. The distance we derived is in good agreement with that of *Hipparcos*, but is more accurately determined. Both the interstellar reddening of 0.15 ± 0.08 mag and a distance of 300 pc are supporting the membership of the Collinder 359.

After subtracting the binary model the residual light curve is obtained and analyzed for additional periodic signals. This analysis shows pulsation with a dominant frequency of about $f_1 = 1.0029 \pm 19$ c/d, corresponding to 0.9971 ± 0.0019 d. We calculate the pulsation constant as 0.479 days. The spectral type of the primary star, the dominant pulsation period and pulsation constant suggest that the more massive primary star is most probably a γ Doradus type pulsator. As it is shown in Fig. 5 the pulsating primary star locates well inside the γ Dor instability strip of the Hertzsprung-Russell

diagram. The primary star seems to pulsate in multiperiodic modes. Further continuous multi-band photometric observations are needed for a better determination of the pulsational periods and amplitudes.

We have suggested preliminary empirical relationships between the pulsation and orbital periods. In addition the pulsation periods of the primaries seem to correlate with their surface gravities and gravitational pull applied by their secondaries. We present some theoretical considerations which explain underlying physics behind these empirical relationships. Moreover, a physical interpretation of the empirical relations correlating the pulsation and orbital periods, and the location in the HR diagram with the evolutionary stage of the γ Dor components in close binaries is certainly needed. Future theoretical pulsational mechanisms for pulsational behavior should take into account quantities such as mass, radius, radius expansion rate and dominant pulsation period. New observations of the binaries containing γ Dor type components will increase the current example to better characterization of this type of asteroseismology.

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Table 6: γ Dor type pulsating stars in eclipsing binary systems. For each system, the columns 2-13 are the orbital period, pulsational period (in days), masses of the primaries, fractional radii, radii in solar units, mean density in CGS, comparison with the Roche radii, pulsation constant (in days), mass of the secondary, orbital separation in solar units, gravitational force exerted by the secondary per gram matter of the primary and

references

System	P_{orb}	P_{puls}	q	M_p/M_\odot	r_p/R_\odot	ρ	$g, \log g$	r_p/r_{Roche}	Q	M_s	$a(R_\odot)$	F/M_p
V551 Aur (δ Sct?)	1.1732	0.12892	0.725		0.221	0.7500		0.539				
VZ CVn	0.84246	1.06876	0.778	1.83	0.3115	0.4985	16.778	0.777	0.635	1.42	5.554	2.663
					1.730		4.225					
V2094 Cyg	8.485376	1.0995	0.4637	1.79	0.1024	0.1673	8.045	0.229	0.379	0.83	24.13	48.5
		1.0428			2.471		3.906		0.359			
V404 Lyr	0.730943	0.50643	0.385	1.35	0.4200	0.3500	12.023					
		4.47356			1.76		4.08					
V2653 Oph	4.39429	0.9971	0.792	1.53	0.1192	0.3248	11.879	0.299	0.479	1.292	15.98	178
					1.88		4.075					
CoRot100866999	2.80889	0.62680	0.65		0.158			0.378				
		0.73210										
CoRot102918586	4.39138	0.81665	0.898	1.66	0.0992	0.5308	16.936	0.256	0.501	1.49	16.53	184
		0.88758			1.64		4.229		0.545			
CoRot102937335	3.97946	1.5772	0.3669		0.1081			0.229				
		1.5748										
CoRot102980178 (γ Dor or SPB?)	5.0548	0.3637	0.206		0.1068							
KIC04544587 (γ Dor or δ Sct?)	2.189094	0.49721	0.808	1.98	0.1677	0.4633	16.403	0.421	0.285	1.60	10.855	538
		0.2883			1.82		4.215		0.165			
KIC11285625	10.79049	1.7937	0.778	1.543	0.0737	0.2275	9.376	0.184	0.720	1.200	28.8	46.6
		1.7627			2.123		3.972		0.708			

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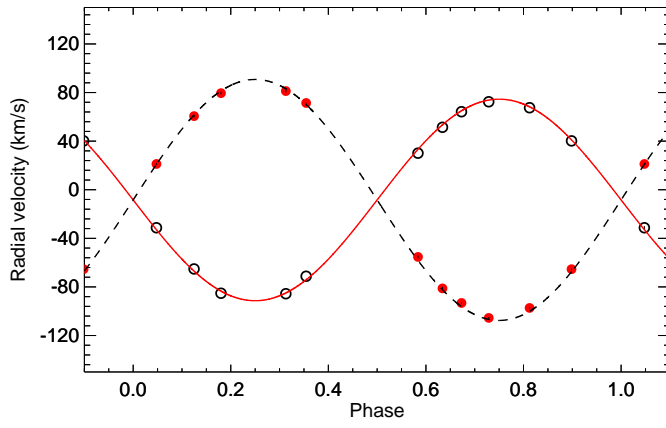


Figure 1: Radial velocities phased with the Eq. 1 of the primary (open circles) and secondary (red filled circles) component of V2653 Oph. Error bars are shown by vertical line segments, which are smaller than symbol sizes. The solid and dashed lines are the computed radial velocity curves for the component stars.

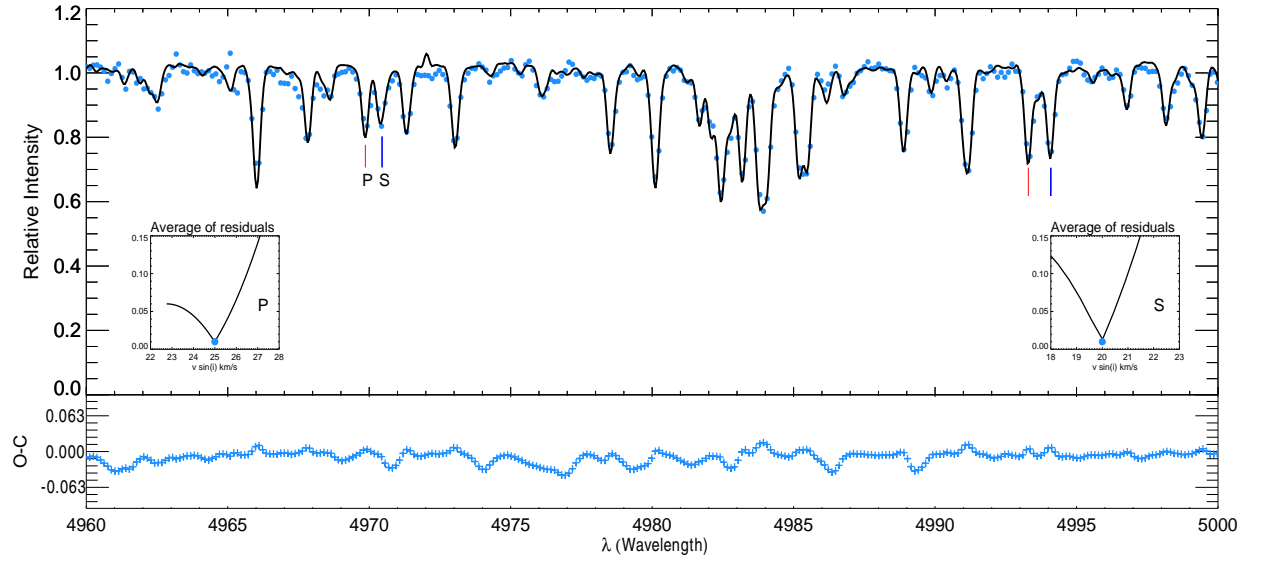


Figure 2: Comparison between the observed spectra of V2653 Oph obtained near quadratures and the best-fitting spectra around $\lambda\lambda$ 4960-5000 lines. The minimum O-C residuals have been obtained for the projected rotational velocities of the more massive and less massive stars as 25 km s^{-1} and 20 km s^{-1} , respectively. In the bottom panel the residuals between the observed and computed spectra are plotted.

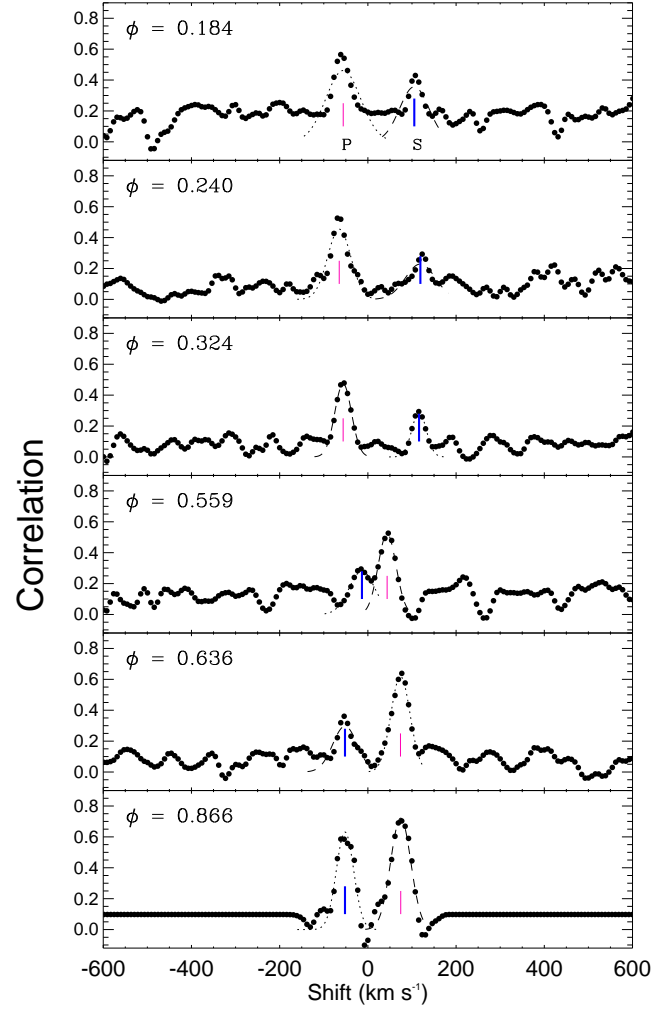


Figure 3: Sample of CCFs between V2653 Oph and the RV template spectrum (ι Psc) around the first and second quadratures.

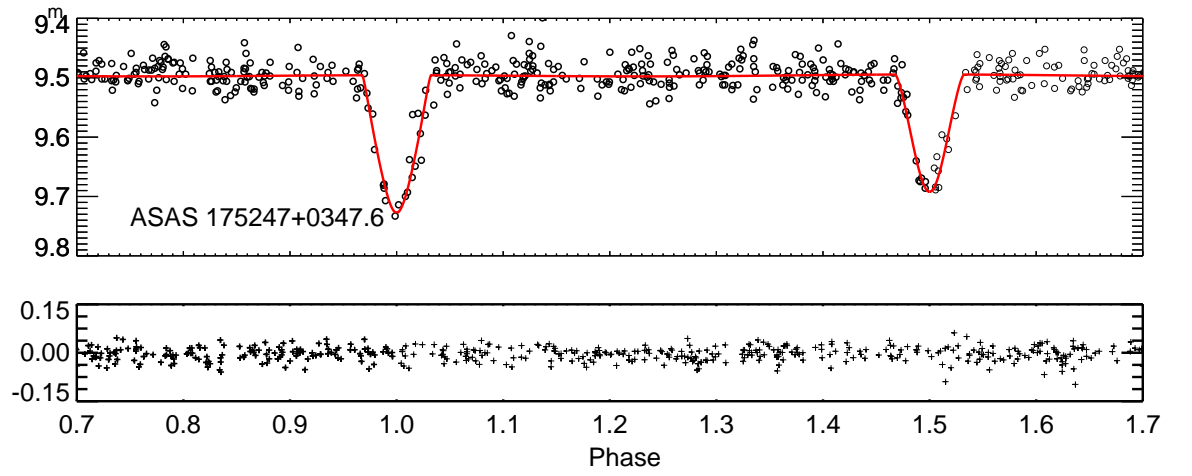


Figure 4: Full light curve of V2653 Oph from *ASAS*. The WD best fit is plotted as blue line and the residuals of the fit are shown in the lower panel.

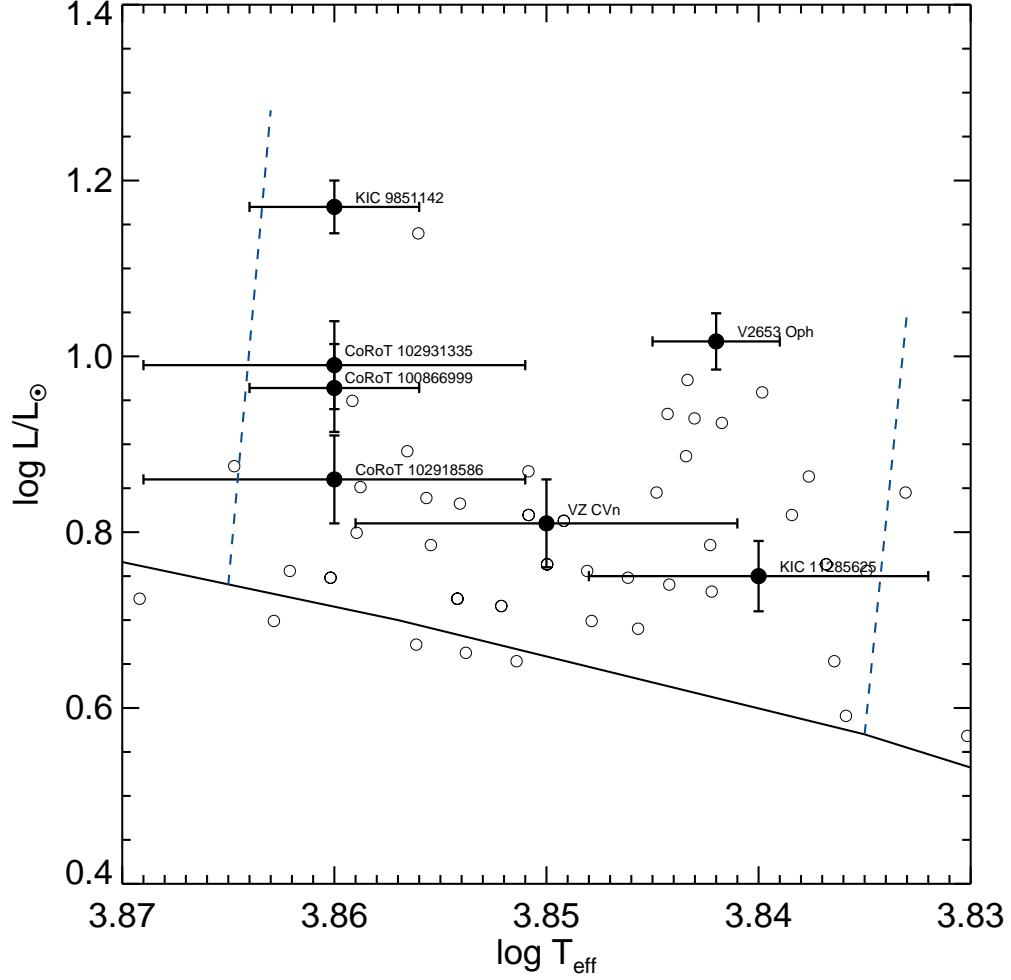


Figure 5: The domain of the γ Dor type pulsating variables in the Hertzsprung-Russell Diagram. The open and filled symbols show the known γ Dor type pulsating single stars taken from the catalog of Henry, Fekel, & Henry (2007) and the primaries of eclipsing binaries collected from individual papers, respectively. The uncertainties for the γ Dor components in eclipsing binaries are also shown. The dashed lines show the theoretical edges of the γ Dor instability strip by Warner, Kaye, & Guzik (2003) and the continuous line corresponds to the zero-age main-sequence.

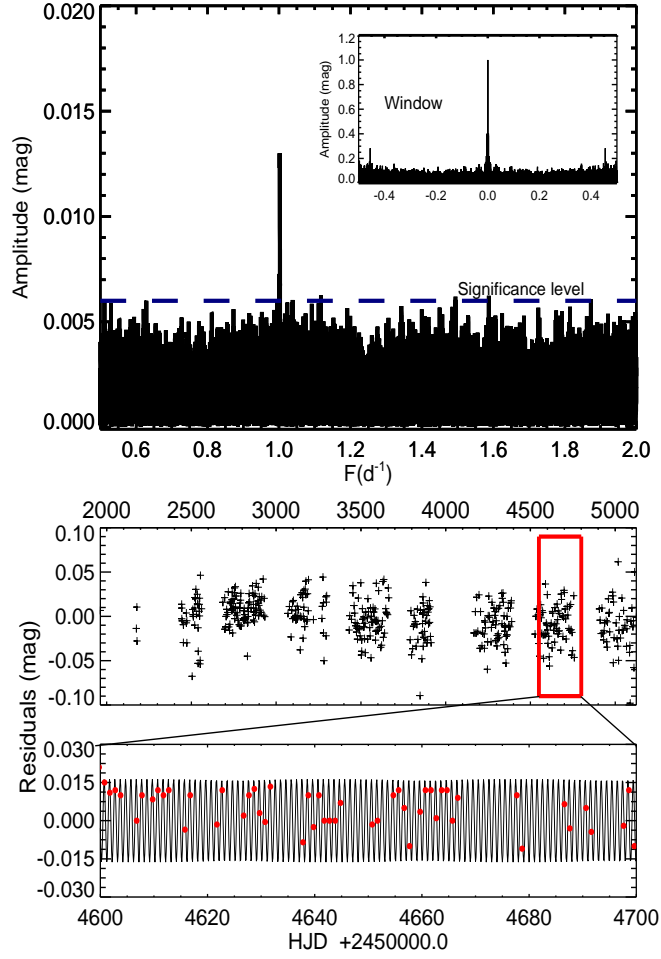


Figure 6: Periodogram of the detected frequency inside the γ Dor frequency range for the system. The significance level (0.006 mag) is indicated.

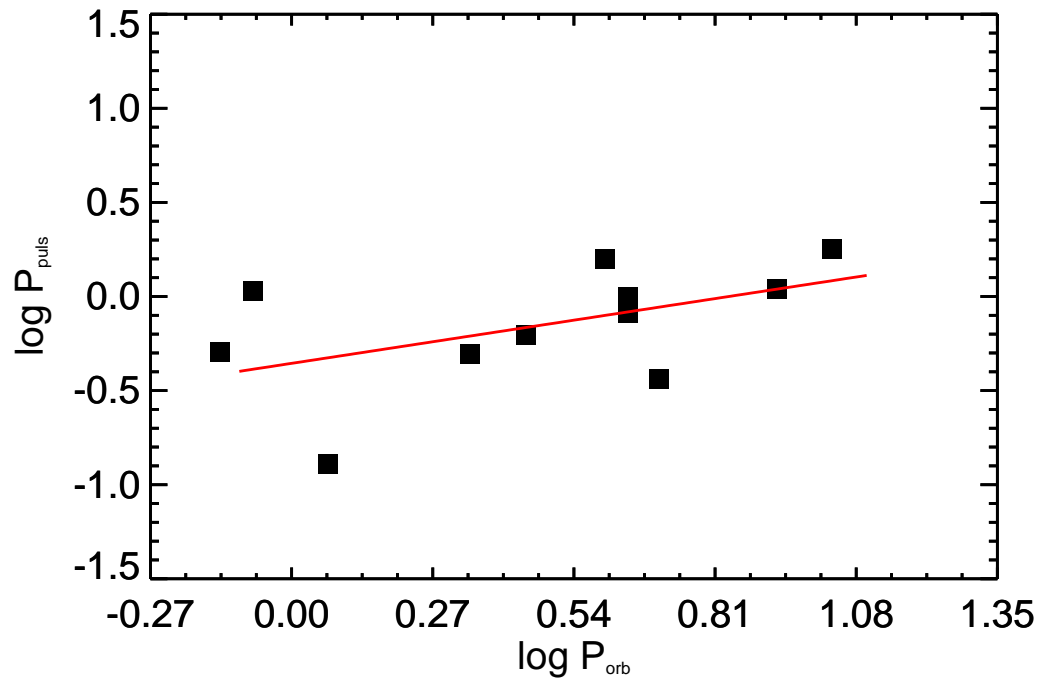


Figure 7: Relation between the pulsational and orbital periods for γ Dor type stars in eclipsing binaries. The solid line represents the best fit with an equation given in the text.

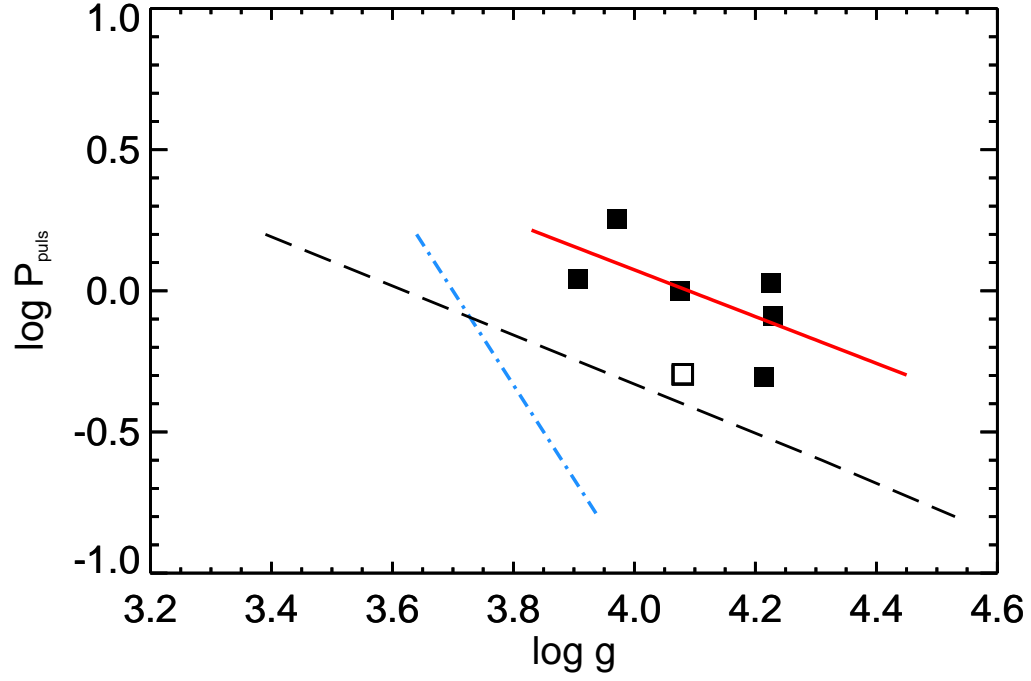


Figure 8: Plot of the pulsational periods versus the gravity of the pulsating stars (filled squares). The solid line represents the best fit between two parameters. The open square symbol shows V404 Lyr for which no spectroscopic observation exists. The relation, P_{puls} - g for the δ -Sct stars (dot-dashed line) (Liakos et al., 2012), and for radially pulsating variable stars (dashed line) (Fernie, 1995) are also shown for comparison. The gravities for radially pulsating stars were shifted one dex for a better comparison.

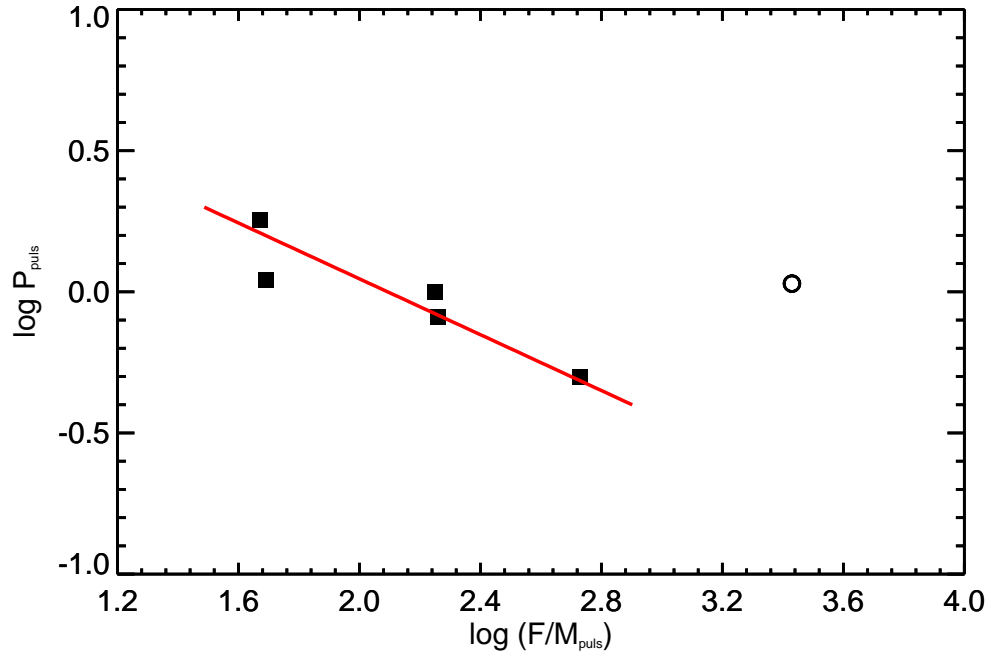


Figure 9: Relation between the pulsational period and the force on the surface of the pulsating star due to the companion per unit mass of the pulsating star for γ Dor type stars in eclipsing binaries. The system VZ CVn (shown by empty circle) is considerably distinguished from the other five systems(see text). The solid line represents the best fit with an equation given in the text, excluding VZ CVn.